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Proposed Specification of EUVL Mask Substrate Roughness

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A revised specification of mask substrate roughness was proposed at the 1st International EUVL Symposium in Dallas in 2002 [1]. This document describes the reasoning behind the proposed revision in more detail.

The specification of mask substrate roughness should be based on its effect on lithographic performance. The effects of mask roughness can be considered according to the spatial frequency. At high frequencies ($f > M\times NA/\lambda$) corresponding to spatial periods too small to be resolved, light is scattered outside the angular acceptance of the camera effectively reducing the reflectivity of the mask. At lower frequencies, $f < M\times NA/\lambda$, light is scattered within the acceptance angle of the camera and can degrade the aerial image quality.

The loss in reflectivity due to high-spatial frequency roughness (HSFR) is given by

$$R/R_0 = \exp(-(4\pi\sigma/\lambda)^2)\,, \quad (1)$$

where R_0 is the peak reflectivity of the coating on a smooth substrate, σ is the HSFR after multilayer coating. The relationship between top surface roughness and substrate roughness depends on the multilayer deposition process and significant smoothing of substrate roughness has been demonstrated [2]. Ultimately the specification of HSFR may be best decided based on the multilayer deposition process. For the present we may adopt a worst-case scenario of no smoothing in which case the top surface roughness is the same as that of the substrate. At very high spatial frequencies, light scattered from the individual interfaces of the multilayer coating no longer adds in phase and the effect of the roughness is diminished. For a typical Mo/Si multilayer coating this occurs at a scattering angle of about 15 degrees from specular and corresponding spatial-frequency of 0.02/nm (50 nm spatial period). If a 2% (relative) loss in reflectivity is allowed due to the HSFR of the mask substrate then one arrives at the following specification,

$$\mathrm{HSFR} < 0.15\,\mathrm{nm} \qquad (0.004/\mathrm{nm} < f < 0.02/\mathrm{nm})\,. \quad (2)$$

The low frequency limit is $M\times NA/\lambda$ rounded down to 0.004/nm (250 nm spatial period), where the magnification M=0.25, NA=0.25 and λ=13.5 nm.

Roughness with spatial frequencies less than MNA/λ scatters light within the acceptance aperture of the camera. In the case of the optics this mid-spatial frequency roughness (MSFR) is the major cause of flare in an EUV lithographic camera. In the case of the mask this roughness results in random phase variations in the aerial image. These phase variations, when coupled with defocus, can result in speckle and line edge roughness (LER) or line width roughness (LWR) for short spatial periods and image placement errors (IPE) for longer spatial periods. These effects are more easily related to the rms surface slope than to surface height errors. From geometric optics, a local slope error σ_s will lead to an image shift of

$$\Delta=2\sigma_s z/M, \quad (3)$$

where z is the defocus distance at the wafer.

Consider first the high spatial frequency slope errors leading to LWR. For a rough surface with an rms slope error of σ_s the random displacements lead to

$$\mathrm{LWR} = 3\sqrt{2}(2s_s)z/M\,. \quad (4)$$

The factor of 3 is there since LWR is typically a 3-sigma value. The factor of √2 assumes that the displacements of the two edges of the line are uncorrelated. For typical substrates it is found that the spatial periods near the camera resolution are the most important contributors to the rms slope error. Since the low frequency limit is less critical a frequency range of 0.1M×NA/λ to M×NA/λ could be used for the high-frequency slope error. This choice has the advantage that the rms slope error over this frequency range can be determined from AFM measurements at selected points on the mask substrate.

The allowable LWR should be small enough that no randomly occurring printable defects are allowed over the area of the mask. For a resolution element of λ/(M×NA) = 216 nm on the mask and a quality area of dimension L=142 mm, the probability of a line width fluctuation large enough to cause a printable defect should be

$$P < \left(\frac{l}{M \cdot \mathrm{NA} \cdot \mathrm{L}}\right)^2 = 2\times10^{-12} \quad (5)$$

Assuming Gaussian statistics, the rms line width fluctuation should be 1/7 of the size of a printable defect which for a 10% ΔCD/CD printability criterion the required LWR<0.04×CD. So for example, for a 32 nm line with a ±90 nm depth of focus, the LWR<1.3 nm and the specification for high frequency mask slope error would be

$$s_s < \frac{M \cdot LWR}{6z\sqrt{2}} = 0.4\,\mathrm{mrad} \quad (0.0004/nm < f < 0.004/nm)\,. \quad (6)$$

The rms slope error for this frequency range could be calculated from an AFM measurement with a scan size of 5 microns. The rms slope can be obtained from the calculated PSD by,

$$s_s^2 = \int_{f_{\min}}^{f_{\max}} (2pf)^3 \mathrm{PSD}(f)\,df \;. \quad (7)$$

Where $f_{\min}$ = 0.0004/nm and $f_{\max}$ = 0.004/nm. The HSFR can also be determined from the same AFM scan if the step size is smaller than 25 nm.

It is important to note that the LWR produced by high frequency mask slope errors will also depend on the partial coherence of the illumination. The high frequency slope error specification could be relaxed for higher values of the partial coherence σ.

Finally at lower frequencies mask slope errors result in image placement errors according to equation (3). For example, if the allowable 3-sigma IPE = 1 nm then the allowable low frequency rms (1-sigma) slope error spec would be

$$s_s < \frac{M \cdot IPE}{6z} = 0.5\,\mathrm{mrad} \;\; (10^{-6}/nm < f < 0.0004/nm). \quad (8)$$

This spatial frequency range corresponds to spatial periods between 2.5 microns and 1 mm. An issue for this range is whether or not it is acceptable to sample the surface roughness at a few points on the mask as is typically done for optical surfaces or whether the entire surface of the mask needs to be inspected for slope errors. The rms slope errors over this frequency range could be determined statistically from roughness measurements using an interference microscope at selected points on the mask surface. Spatial periods longer than 1 mm would be covered by the mask flatness specification.

[1] E.M. Gullikson, J. Taylor, K. Blaedel, S. Baker, C. Larson, *1st International EUVL Symposium*, Dallas, TX 2002.

[2] E. Spiller, S.L. Baker, P.B. Mirkarimi, V.Sperry, E.M. Gullikson, D.G. Stearns, *Appl. Opt*. **42**, 4049 (July 2003).

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